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An Experimental and Theoretical Investigation of Optogalvanic Effects

Final Report for the period June 15, 1981 - June 14, 1984

James. E. Lawler

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of a mechanism for amplifying optogalvanic effects, and (3) the development of powerful new gas discharge diagnostics based on optogalvanic detection of Rydberg atoms. The amplified optogalvanic effects, which occur in the cathode fall, constitute a promising area for further research.

A detailed rate equation model for the 594.5 nm optogalvanic effect in the Ne positive column discharge is described. The model relates the absolute magnitude of the optogalvanic effect to known rate constants over a wide range of discharge conditions. The 594.5 nm optogalvanic effect is modeled in Ne discharges with current densities from 0.03A/cm^2 to 0.5A/cm^2 and with pressures from 1.0 to 10.0 Torr. The ionization balance and power balance of the discharge is mapped over the entire regime. The range of parameters covers the transition from a discharge sustained primarily by single-step electron impact ionization to a discharge sustained primarily by two-step ionization processes involving metastable atoms in $2p^3s$ configuration. The power balance of the discharge is dominated by wall losses of atoms excited to the $2p^53s$ configuration at all currents and pressures studied.

An anomalously strong optogalvanic effect is observed on the 594.5 nm Ne transition in the obstructed glow discharge. An obstructed glow discharge occurs between plane parallel electrodes at low pressure. It corresponds to operation on "left hand" side of Paschen curve. The cathode fall region is essentially the entire discharge. Optogalvanic effects near the cathode surface are as much as 100 times stronger than typical effects in the positive column. The effects are amplified by the electron avalanche which occurs in the cathode fall. The magnitude of an optogalvanic effect is measured as the change in electrical power delivered to a series resistor divided by the absorbed laser power. This dimensionless ratio is, within limits, independent of laser power, nonessential geometrical factors of the discharge, and the electrical circuit driving the discharge. The ratio is observed to be as large as -470 for the 594.5 nm optogalvanic effect in the obstructed glow discharge. These amplified optogalvanic effects are a promising topic for further research.

New gas discharge diagnostics involving optogalvanic detection of Rydberg atoms are described. Rydberg atoms are ideal probes because they are easily perturbed by the discharge environment and because the effect of a perturbation on a Rydberg level is straightforward to interpret. Optogalvanic detection of a transition to a Rydberg level is essential because the Rydberg atoms are collisionally ionized before they fluoresce. Linear Stark effects in Rydberg levels are used to accurately measure space charge fields in diffuse discharges. The linear Stark effects are dramatic: they are spread over tens of wavenumbers at modest fields because of the large size of the Rydberg atoms and because of the small energy gap between states of opposite parity. Stark broadening due to fluctuating fields produced by ion collisions is also observed. The Rydberg atom diagnostics are broadly applicable because every atom has Rydberg levels. The diagnostics are useful over a wide range of electric fields because the linear Stark effect scales with the square of the principle quantum number. These Rydberg atom/optogalvanic diagnostics are particularly well suited to research on the cathode fall region because of amplification of optogalvanic effects in the cathode fall.

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1. Introduction

An optogalvanic effect is a change in the conductance of a gas discharge caused by illumination with radiation having a wavelength corresponding to an atomic or molecular transition. The radiation perturbs the population of at least two atomic or molecular levels in the system. These different levels will in general have different ionization or attachment rates, hence the radiation perturbs the ionization balance of the discharge. A change in the ionization balance results in a change in the conductance of the discharge.

Any reaction, which is important in the ionization balance of the discharge, can produce an optogalvanic effect. Electron impact ionization, associative ionization, chemionization, and ionizing collisions between pairs of excited atoms can all be important. Electron attachment reactions can also be important in molecular systems. Optogalvanic effects in the cathode region can be caused by changes in the excited atom flux on the cathode, which results in a change in the electron emission rate from a cold cathode.

Some optogalvanic effects correspond to an increase in discharge conductance; we call such effects positive. Other effects correspond to a decrease in discharge conductance; we call these effects negative. The most common type of negative optogalvanic effect is due to the depletion of metastable atoms by optical excitation to a level which radiates directly or indirectly to the ground state. Effects of this type were the first optogalvanic effects observed.^{1,2,3} Metastable atoms play a key role in ion production in many discharges, thus the effects can be large even with an incoherent source of radiation.

Optogalvanic effects also occur near the cathode surface. These effects occur because atoms in different excited levels have different probabilities of releasing secondary electrons from the cathode. Atoms in a metastable level, which are in the cathode fall region of the discharge, may diffuse to the cathode and strike the cathode. Metastable atoms are very efficient at releasing secondary electrons from the cathode. Atoms in short lived resonance levels, which are in the cathode fall region of the discharge, will likely radiate before they strike the cathode. The vuv radiation will be repeatedly reabsorbed until a photon is emitted far from line center. A photon far from line center will not be reabsorbed in the discharge and it may strike the cathode. Ultraviolet photons are in general far less efficient at releasing secondary electrons than metastable atoms. Hence a negative optogalvanic effect can be produced by using a laser to drive atoms from a metastable level to a resonance level.

Optogalvanic effects in the cathode region are of particular interest because such effects are as much as a factor of 100 larger than effects in the positive column region.⁴ The effects near the cathode surface are amplified by the cathode fall. Most (> 90%) of the discharge current at the surface of a cold cathode is carried by returning ions rather than emitted electrons. Hence the loss of one emitted electron results in the loss of all subsequent ionization.

The goal of this research is to apply optogalvanic effects in a pulsed power switch. A fast repetitive opening switch will be quite useful in pulsed power technology.⁵ The development of such a repetitive opening switch will make inductive energy storage systems practical for many pulsed power applications. A simple inductive energy storage system is shown in Fig 1. The inductor current is built up slowly over a relatively long period

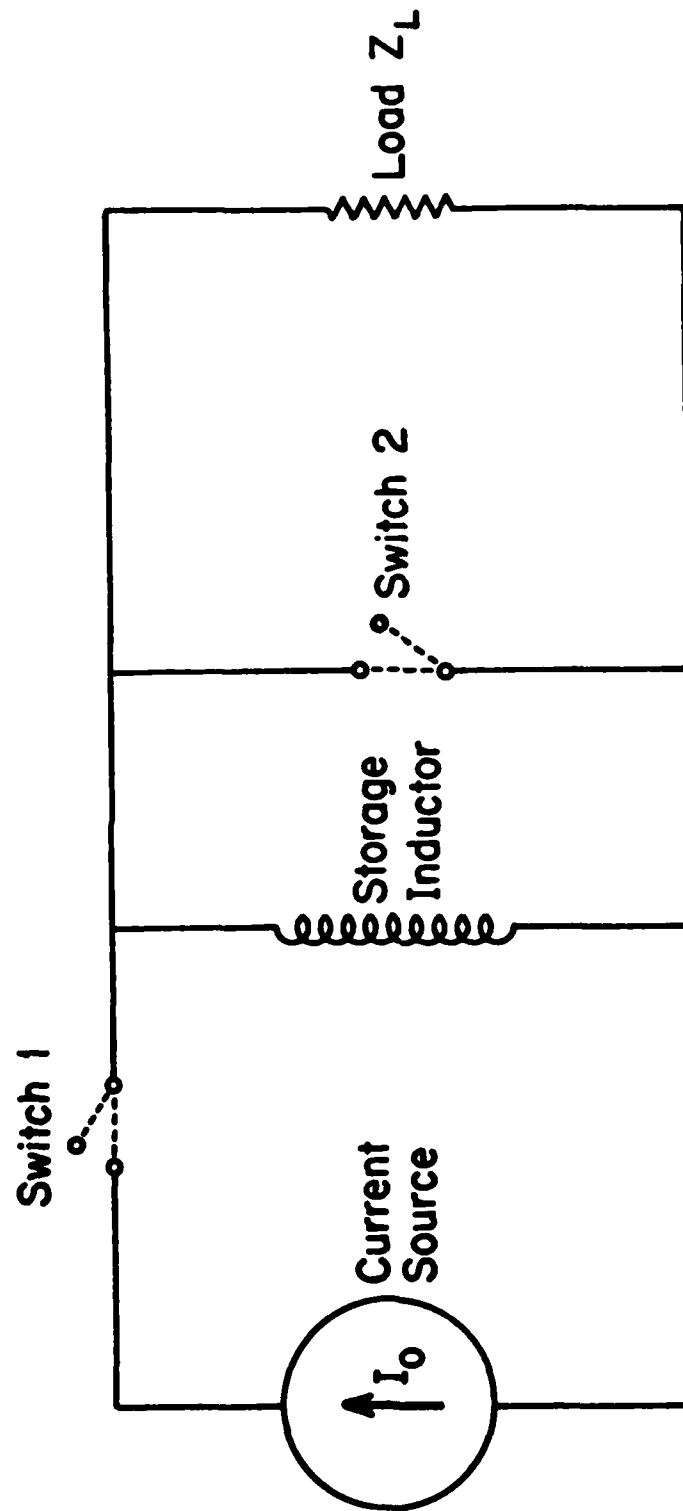


Figure 1. A simple inductive energy storage circuit for pulsed power applications.

of time through switch 1, which could be a vacuum interruptor switch. Switch 2 is closed, after the inductor current is built up, to carry the inductor current while switch 1 recovers. Switch 2 is the proposed diffuse discharge switch. Switch 2 is opened in $1\mu\text{s}$ or less to deliver the entire inductor current to the high impedance load in a burst mode or in a single shot mode. The research described in this document is directed toward the development of switch 2, the fast repetitive opening switch.

The concept of using a laser to control switch 2 is attractive for several reasons. The laser system can be remote from switch 2. The laser will provide precise timing of parallel systems. The laser can have a substantial effect on a discharge per unit of energy absorbed, because the laser can selectively perturb key species. An important question is whether the laser should be used to sustain the discharge in switch 2 during its conducting phase, or used to perturb the discharge in switch 2 to trigger its opening phase. It is apparent that lasers can initiate discharges, and that sufficiently powerful lasers can sustain discharges. It is not so apparent, but none-the-less true, that a laser can perturb and extinguish a discharge. The latter scenario, of extinguishing the discharge using a laser, is the thrust of this investigation. Laser light is expensive in terms of capital equipment and in terms of energy. We believe that it is desirable to use the laser only during the opening phase of switch 2. It is essential that the energy required to run the laser be very much smaller than the energy delivered to the load. The potential advantage of the latter scheme over the former scheme, of using the laser to sustain the discharge, is more significant if switch 2 must carry current for a substantial time.

The load impedance of Fig. 1 may be capacitive, resistive, or inductive depending on the particular application. A capacitive load represents the "easiest" load to the switch: an inductive load represents the "most difficult" load to the switch. The ease or difficulty refers to the voltage the switch must sustain during its opening phase. We assume, at this stage of our investigation, a resistive load because it is amenable to a simple steady state analysis. Figure 2 is a plot of the voltage versus current for switch 2, with a load line representing the external circuit of Fig. 1 with switch 1 open. The intersection, labeled B, of the load line with the voltage versus current curve for the discharge is a stable operating point. The intersection labeled A is unstable. Most of the inductor current is delivered to the low impedance discharge when the system is at intersection B. A relatively small perturbation to the discharge which shifts the voltage versus current characteristics to the dotted curve eliminates the stable operating point and delivers all of the source current to the load. This simple analysis illustrates the desirability of a discharge with voltage versus current characteristics having a large negative slope or negative dynamic resistance.⁶ There is a second reason why it is desirable for the discharge to have a large dynamic resistance. If the power deposited by the laser is small ($<10\%$) compared to the total dissipated in the discharge, then it should be possible to model the optogalvanic effect by applying first order perturbation theory to the rate equations which describe the discharge. The magnitude of the effect in a first order analysis is proportional to the product of the absorbed power and the dynamic resistance.⁷ Hence a discharge with a large dynamic resistance is intrinsically easy to perturb.

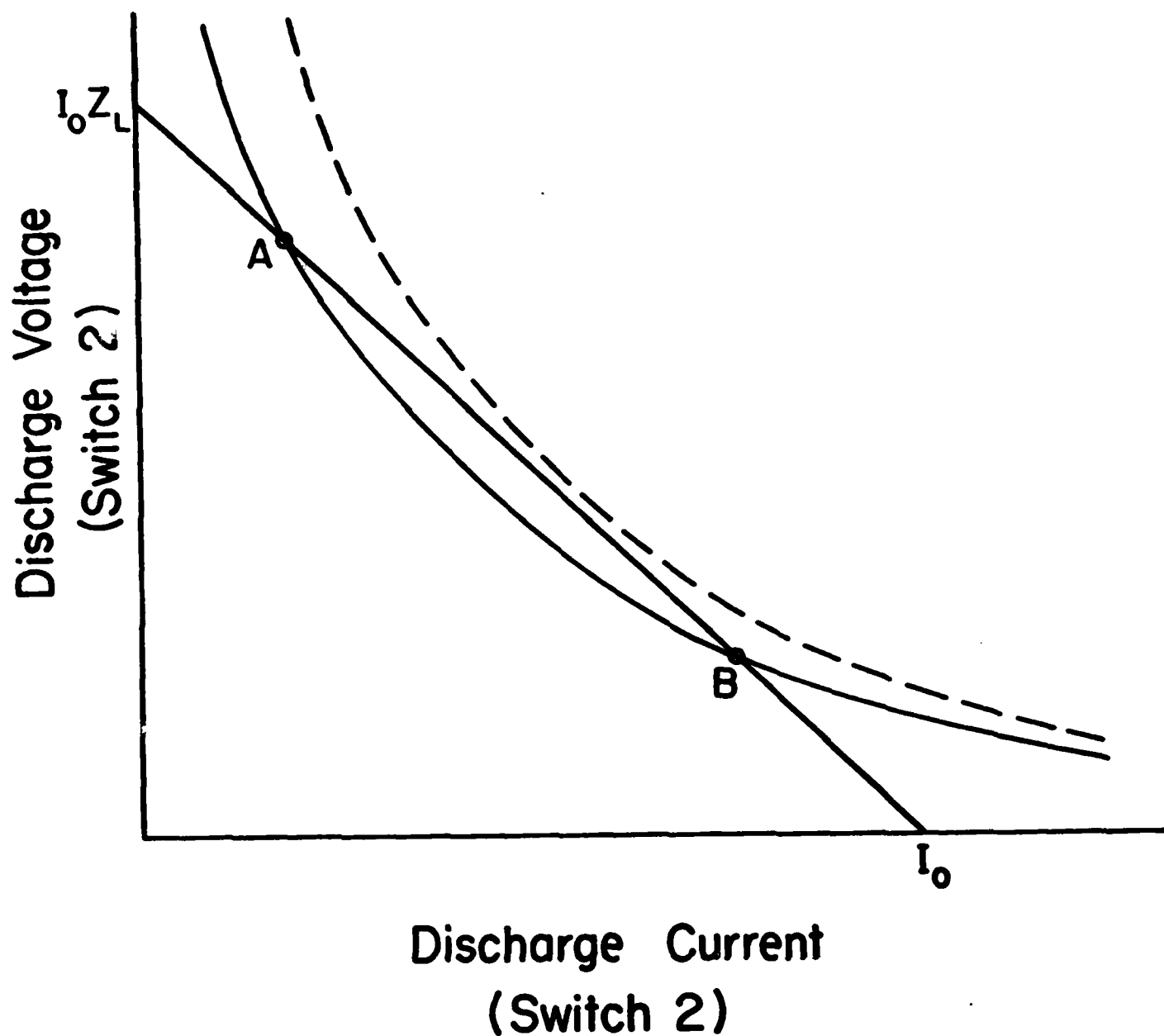


Figure 2. Load line analysis of the inductive energy storage circuit of Fig. 1 with Switch 1 open. The solid curve represents the voltage versus current of Switch 2 without laser illumination. The dotted curve represents the voltage versus current of Switch 2 with laser illumination. The solid straight line is a load line.

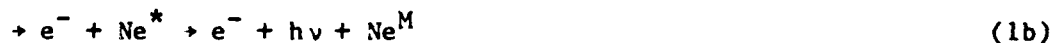
A large negative dynamic resistance at the operating point on the load line does have a disadvantage. The discharge is macroscopically unstable, and it will not be easy to put many switches in parallel. The discharge may also be subject to microscopic or internal instabilities. Hence it may be necessary to have a positive dynamic resistance at the operating point on the load line.

The research described in this document has led to: (1) a better understanding of interaction between intense laser light and gas discharges, (2) the development of important new gas discharge diagnostics, (3) the identification of the cathode fall region as a particularly promising area for further research on optogalvanic effects.

II. Steady State Optogalvanic Effects in the Positive Column

Steady state effects are somewhat more amenable to theoretical interpretation than transient effects. Our research on steady state optogalvanic effects has provided us with a theoretical framework for modeling transient effects. We have studied optogalvanic effects in Ne positive column discharges. We successfully modeled a strong negative optogalvanic effect at 594.5nm over a wide range of discharge conditions.⁸

The levels in Ne which play a role in the 594.5nm optogalvanic effect are indicated in Fig. 3. Neon atoms are excited by the laser from the $2p^5 3s (1s_5)$ metastable level to the $2p^5 3p (2p_4)$ level. The $2p^5 3p (2p_4)$ level has a radiative lifetime of 20ns, atoms in this level radiatively decay primarily to non-metastable levels.⁹ Approximately 46% decay to the $2p^5 3s (1s_2)$ which has a vacuum radiative lifetime of 1.5ns. Approximately 33% of the atoms in the $2p^5 3p (2p_4)$ radiatively decay to the $2p^5 3s (1s_4)$ level which has a vacuum lifetime of 21ns. The remaining 21% of the atoms excited by the laser to the $2p^5 3p (2p_4)$ radiate at the laser wavelength and decay back to the $2p^5 3s (1s_5)$ level. The effective radiative lifetimes of the resonance $1s_4$ and $1s_2$ levels are much longer than their vacuum lifetimes due to radiation trapping. The effective radiative lifetimes are still shorter than the diffusion limited lifetimes of the metastable atoms. The negative optogalvanic effect on the 594.5nm transition is caused by the depletion of the long lived metastable Ne atoms which play a key role in the multistep ionization processes. Typical multistep processes are



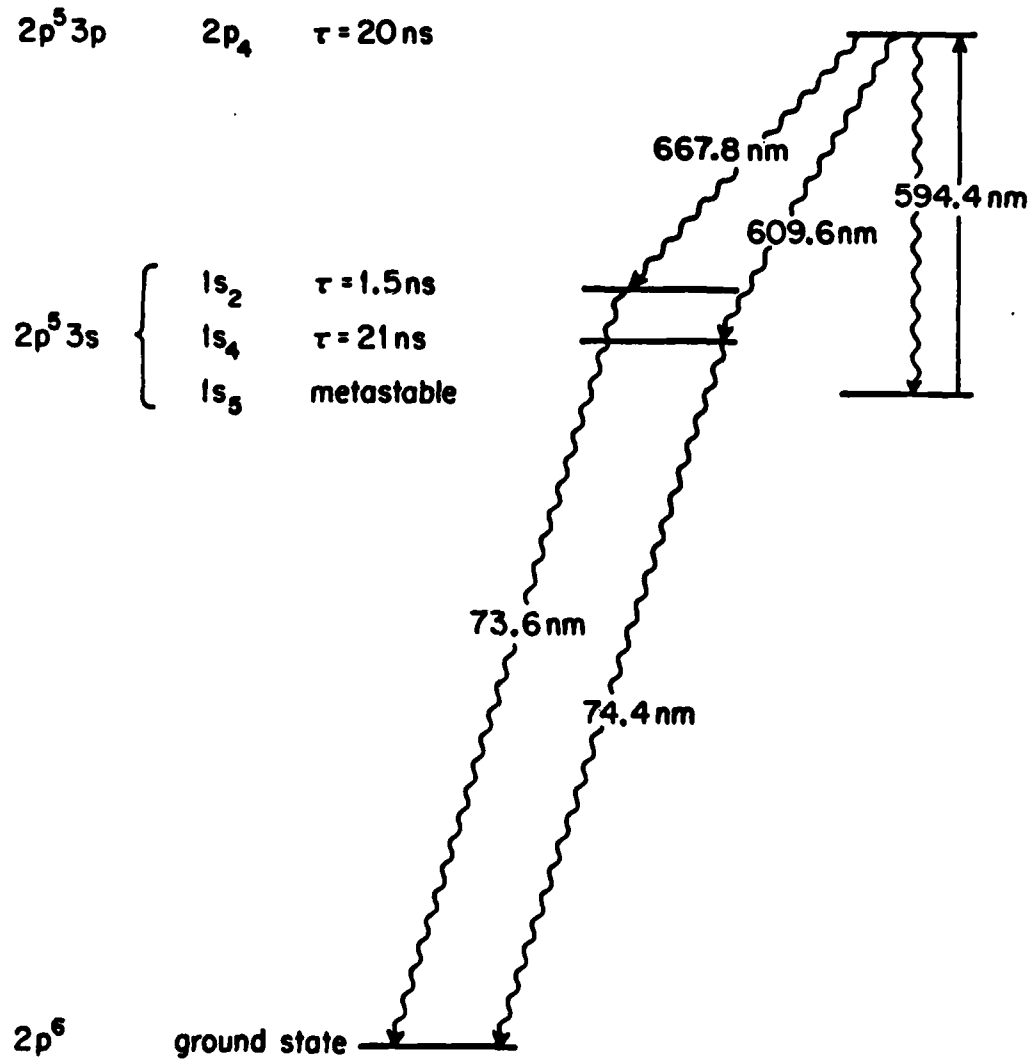


Figure 3. Energy level diagram of Neon. Only levels important in the 594.4nm optogalvanic effect are shown. The straight vertical line represents absorption of a laser photon. The curved lines represent fluorescence.

where Ne^M represents a metastable Ne atom, and Ne^* represents a Ne atom in a level which radiates to a metastable level.

A model of an optogalvanic effect is a model of a laser induced perturbation to a discharge. It is essential to start from a good overall description of the discharge before one attempts to model a perturbation to the discharge. We believe that careful determinations of the dominant mechanisms of ion production and loss, and the dominant mechanisms of the energy balance in the discharge are essential in modeling an optogalvanic effect. We have thoroughly characterized the ionization balance and energy balance of the Ne positive column discharge. The studied regime covers the transition from a discharge sustained primarily by single-step electron impact ionization to a discharge sustained primarily by two-step ionization via the $2p^53s$ metastable levels. The global power balance of the discharge is dominated by wall losses of atoms excited to the $2p^53s$ levels at all pressures and currents studied.

Our determination of the relative importance of single-step versus two-step ionization in the Ne positive column discharge has implications for a diffuse discharge switch. We found that under certain conditions over 90% of the ionization in the discharge was through the $2p^53s \ ^3P$ term. The development of a laser controlled diffuse discharge switch requires that a discharge be identified in which a single process involving very few levels dominates ion production or loss. A laser can then be used to selectively perturb one or a few levels and produce a substantial change in the discharge conductivity.

The loss of ion-electron pairs in the discharge we studied is dominated by diffusion to the wall. The discharge is far from local thermodynamic equilibrium (LTE) because wall losses dominate and recombination is

unimportant. Large optogalvanic effects (especially large negative effects) are not likely to occur in discharges near LTE. If a discharge is near LTE, then the effect of the absorption of laser light by atoms or molecules is usually to heat the electron gas through superelastic collisions with the excited species.¹⁰ Hence we believe that any discharge likely to be useful as a laser controlled switch will be far from LTE.

A diffuse discharge sufficiently far from LTE has an electron energy distribution determined solely by E/N , the electric field divided by density of ground state atoms. This is not the case if the discharge is intense and near LTE because superelastic electron collisions with excited atoms will affect the distribution function. The most important single approximation we have tested in our model is the description of the laser induced change in the electron distribution function. We have verified that the electron distribution function is primarily affected by the change in E/N and not by the change in excited atom density. The approximation has worked well in discharges with current densities in excess of 1.0A/cm^2 .

Our research on steady state optogalvanic effects in the positive column led to a detailed quantitative understanding of a strong negative effect in Ne over a wide range of discharge conditions. The regime studied covered the range from a discharge sustained primarily by single-step electron impact ionization to a discharge sustained primarily by two-step ionization. The power balance of the discharge is dominated by loss of atoms in the metastable and resonant levels of the $2p^53s$ configuration, the lowest excited configuration of Ne. The determination of the dominant mechanisms in the ionization and power balance, as well as detailed quantitative modeling of the 594.5nm optogalvanic effect, provides the

necessary theoretical framework for understanding optogalvanic effects in many discharges.

III. Steady State Optogalvanic Effects in the Cathode Fall

Our research on steady state optogalvanic effects in the cathode fall region has identified a mechanism for discharge amplification of optogalvanic effects. Laser photons are expensive; the capital cost and energy cost of laser radiation is high. It is therefore essential that the laser light be used very efficiently in any laser controlled switch.

We have measured anomalously strong optogalvanic effects in an obstructed glow discharge. An obstructed glow discharge occurs between plane parallel electrodes at low pressure. The discharge corresponds to operation on the "left side" of the Paschen curve where the breakdown voltage increases with decreasing pressure.¹¹ In order to compare optogalvanic effects in different types of discharges we introduced a parameter characterizing the strength of a steady state optogalvanic effect. The parameter is the dimensionless ratio formed by dividing the change in power delivered to the ballast (or load) resistor by the absorbed laser power. This dimensionless ratio is, within limits, independent of laser power, nonessential geometrical factors of the discharge, and the electrical circuit driving the discharge. The magnitude of the ratio is typically 5 or less in positive column and hollow cathode discharges. We have measured optogalvanic effects in an obstructed glow discharge for which this ratio is $-470.^4$

The 594.5nm optogalvanic effect in the obstructed glow discharge is two orders of magnitude larger than the 594.5nm effect in the positive column discharge. The dramatic difference in the magnitudes of the effects is evidence that the kinetics of the 594.5nm effect in the obstructed glow discharge is different from the kinetics of the 594.5nm effect observed in other types of glow discharges.

Metastable atom bombardment is a mechanism for electron emission from a cold cathode. Helm reports data on the relative importance of metastable bombardment in electron emission from a cold cathode in an Ar discharge.¹² He finds that metastable bombardment accounts for 25% of the electron emission from the cathode at a pressure of 0.05 Torr and at a current density in the mA/cm² range. Helm also finds that uv resonance photon bombardment of the cathode accounts for less than 0.1% of the electron emission from the cathode. The observations are consistent with a low electron emission coefficient for uv photons and a high electron emission coefficient for metastable atoms. Thus, the depletion of metastable atoms near the cathode by laser excitation to a level that cascades to the ground state gives rise to a negative optogalvanic effect. The optogalvanic effects we observe in the obstructed glow discharge are due to laser depletion of metastable atoms that would otherwise collide with the cathode and release electrons. This interpretation is consistent with the unusually large size of the effects and the dependence of the effects on cathode material.

The cathode fall region of an obstructed glow discharge is essentially the entire discharge. Optogalvanic effects in the cathode fall region have a "built in" gain mechanism. Only a small fraction of the total discharge current at a cold cathode is carried by emitted electrons, most of the current is carried by returning positive ions. If the electrons carry 10% of the current at the cathode, then the loss of one emitted electron per unit time may reduce the total current by 10 charges per unit time. This reduction is due to the loss of production of subsequent ion-electron pairs. Optogalvanic effects in the cathode region may also scale more favorably to high current density than effects in other types of glow discharges. The

low electron density in the cathode fall region reduces competition between electron collisions and laser photons in driving a process.

The discovery of amplified optogalvanic effects in the cathode fall region has important implications for laser controlled diffuse discharge switches. The amplified effects will also be an important tool for studying the cathode fall. The cathode fall region of any diffuse discharge switch, electron beam controlled or laser controlled, is a very important but poorly understood region. Detailed studies of these amplified effects will lead to a more quantitative understanding of the cathode fall region.

IV. Rydberg Atom/Optogalvanic Diagnostic

The cathode fall region is the most dynamic and most difficult to model region of a diffuse discharge. The cathode fall region has a very high and rapidly changing E/N (electric field divided by ground state atom density). A result of this is the failure of the electron energy distribution function in the cathode fall region to be in hydrodynamic equilibrium with the local E/N . It is not satisfactory to use electron drift velocities, first Townsend coefficients, and excitation coefficients, which are determined as a function of E/N in equilibrium, to describe the behavior of the electrons if they are not in hydrodynamic equilibrium with the local E/N . Early models of the cathode fall used unsatisfactory approximations of this type.¹³

A recent European collaboration tackled the problem of determining the electron energy distribution function in the cathode fall.¹⁴ They start from the Boltzman equation and use certain analytical approximations and Monte Carlo simulations to compute electron energy distribution functions in rare gas discharges. They have also developed an "Effective Field Model" which is particularly simple and attractive. Their calculations, including the effective field model, have not been adequately tested in comparison to experiments. We wish to emphasize that thorough research on the cathode fall region is important not only for understanding amplified optogalvanic effects but also for understanding the role of the cathode fall region in other switches such as electron beam controlled devices.

We believe that the tunable dye laser is a uniquely powerful tool for detailed quantitative studies of the cathode fall region. A key measurement in cathode fall studies is the determination of the electric field as a function of distance from the cathode surface. We developed a laser diagnostic which enables us to make accurate spatially resolved electric

field measurements in the cathode fall region. Our laser diagnostic is based on optogalvanic detection of Rydberg atoms. The large size of Rydberg atoms and small energy separation between Rydberg levels of opposite parity produce dramatic linear Stark effects at modest fields. The "size" of a Rydberg atom is $n^2 a_0$ where n is the principle quantum number and a_0 is the Bohr radius. The separation of adjacent levels of opposite parity for a constant quantum defect is proportional to n^{-3} . The Stark effects are straightforward to compute, hence an experimental Stark spectra can determine an electric field to high accuracy.

The Rydberg atoms in a discharge environment are collisionally ionized at a much higher rate than their radiative decay rate. Optogalvanic detection is therefore an ideal method of detection. We found that the best sensitivity is achieved by laser excitation of atoms from a highly populated metastable level to a Rydberg level. One method of excitation of Rydberg levels involves using a frequency doubled dye laser. We excite atoms from the He 2^1S metastable level to the 11^1P level which is mixed by the Stark effect with the 11^1D , 11^1F , ..., 11^1N levels. The metastable level is well below the threshold for associative ionization while the $n = 11$ levels are well above the threshold. Hence optogalvanic effects are efficient and prompt.

We also have used two-step excitation in Ne. The two-step method does not require frequency doubling, but does require two independently tunable dye lasers. We first excite atoms from the $2p^5 3s \ ^3P_2$ metastable level to the $2p^5 3p \ ^3P_1$ level using 588.0 nm laser light and subsequently excite the atoms to the $2p^5 \ 11d'$ Stark manifold using 439.3 nm laser light. The prime notation ($11d'$, $11f'$...) refers to the ion core coupling of $^2P_{1/2}$. The two step method has an important advantage in that we measure the electric field

at the intersection of two laser beams. A single step excitation with a frequency doubled dye laser averages the field along the laser beam. The two step measurements in Ne enabled us to determine the field along a well defined path from anode to cathode and integrate the field along this path. The integral agreed with the digital voltmeter reading of the discharge voltage to 1%.

Cathode electric field measurements have been traditionally performed using an electron beam deflection technique.¹⁵ Our spectroscopic approach has very important advantages. The spectroscopic measurements are much easier to perform in a high purity system. This is significant because almost all of the existing cathode fall region electric field data from electron beam measurements was not taken in clean discharges.¹⁵ The spectroscopic technique is truly nonperturbing; the field is measured when the atoms absorb laser radiation which occurs before they are collisionally ionized. The spectroscopic approach will work at higher pressures and current densities than the electron beam approach. The spectroscopic approach has the potential to achieve spatial resolution of a few microns and temporal resolution of a few nanoseconds.

Electric field measurements as a function of position in the cathode fall region provide a wealth of information on the structure of the cathode fall. Drift velocities of atomic ions in their parent gas are limited by symmetric charge exchange. The drift velocities are known to a very high E/N .¹⁶ If the fractional change in E/N per mean free path of the ions is small, then the ions may be assumed to be in hydrodynamic equilibrium with the local E/N . An ion essentially starts from rest after each charge exchange collision. The pressure thickness product of a cathode fall is typically 1 Torr-cm, which must be compared to a typical symmetric charge

exchange cross section of 10^{-14} cm^2 . The symmetric charge exchange cross sections are only very weakly dependent on energy. An atomic ion undergoes approximately 300 charge exchange collisions in the cathode fall region. The only part of the region where the ions might not be in hydrodynamic equilibrium with the local E/N is very close to the negative glow - cathode fall boundary where the percentage change in field per ion mean free path can be large. The situation for the ions is much different than the situation for the electrons in the cathode fall, which are not in hydrodynamic equilibrium.

The derivative of the electric field with respect to distance from the cathode provides a space charge density from Poisson's equation. The space charge density is dominated by the positive ion density through most of the cathode fall region. Hence the derivative provides the positive ion density. The positive ion density and drift velocity are used to deduce the fractions of the total discharge current carried by ions and electrons as a function of distance from the cathode. This information can be used to deduce the ion production rate as a function of distance from the cathode using the ion continuity equation. All quantities derived from the electric field measurements are dependent on having accurate spatially resolved field measurements. We believe that optogalvanic detection of linear Stark effects in Rydberg atoms can provide field measurements to 1% or better. The determination of electric fields, of ion drift velocities, of ion densities, of fractions of discharge current carried by ions and electrons, and of ion production rates as a function of distance from the cathode will provide a very important test of modern cathode fall models.

V. Transient Optogalvanic Effects

Studies of transient optogalvanic effects have provided an unambiguous demonstration that the effects do occur on a submicrosecond time scale. The temporal and spatial dependence of the effects contains a great deal of information on the structure of the cathode fall region. Oscilloscope traces of representative signals are shown in Figs. 4 and 5.

It is not possible to perform detailed quantitative calculations of transient effects until we have a more complete model of the unperturbed cathode fall region. A qualitative explanation of features is currently possible. The 388.9 nm transition of He corresponds to excitation from the 2^3S metastable level to the 3^3P level. Atoms excited to the 3^3P level are either associatively ionized (Hornbeck-Molner process) or radiatively decay back to the 2^3S level. The rates for various processes are known.¹⁷ The pure Russell Saunders coupling of He prevents radiation from the 3^3P level to singlet levels. Collisions with ground state atoms transfer some atoms to the 3^3S and 3^3D levels but not to singlet levels because of the spin selection rule. The electron density is too low in the cathode fall for electron collisions to transfer any significant fraction of atoms in triplet levels to singlet levels. Associative ionization produces the fast positive optogalvanic effect in the oscilloscope traces which corresponds to an increase in the discharge conductance. The loss of some metastables from this process produces a slower negative effect which is small and not visible in the traces of Fig. 4. The slower negative effect is attributed to the loss of metastable flux on the cathode and loss of some electron emission from the cathode.

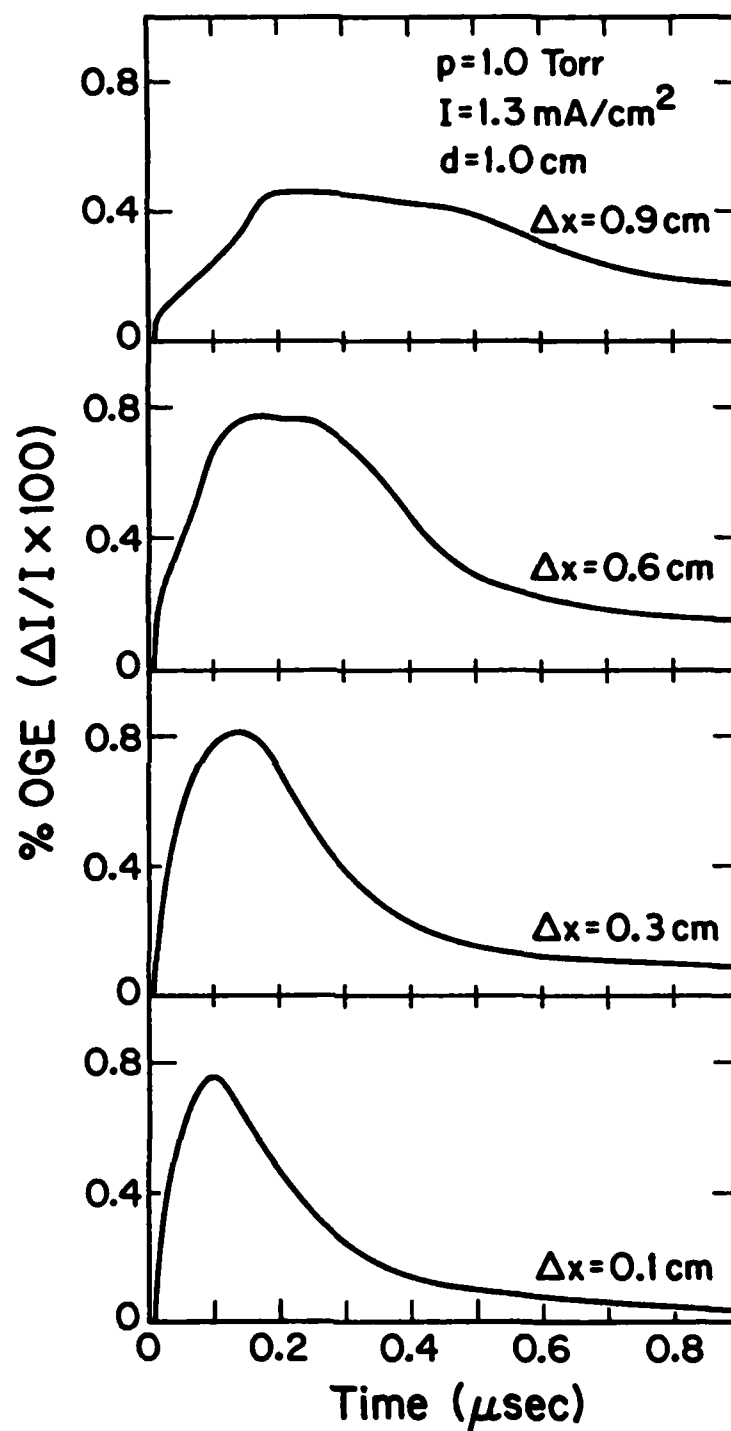


Figure 4. Time resolved optogalvanic effect observed at 388.9 nm in a Helium discharge. The laser is focused a distance Δx from the cathode. The anode-cathode separation is 1.0 cm.

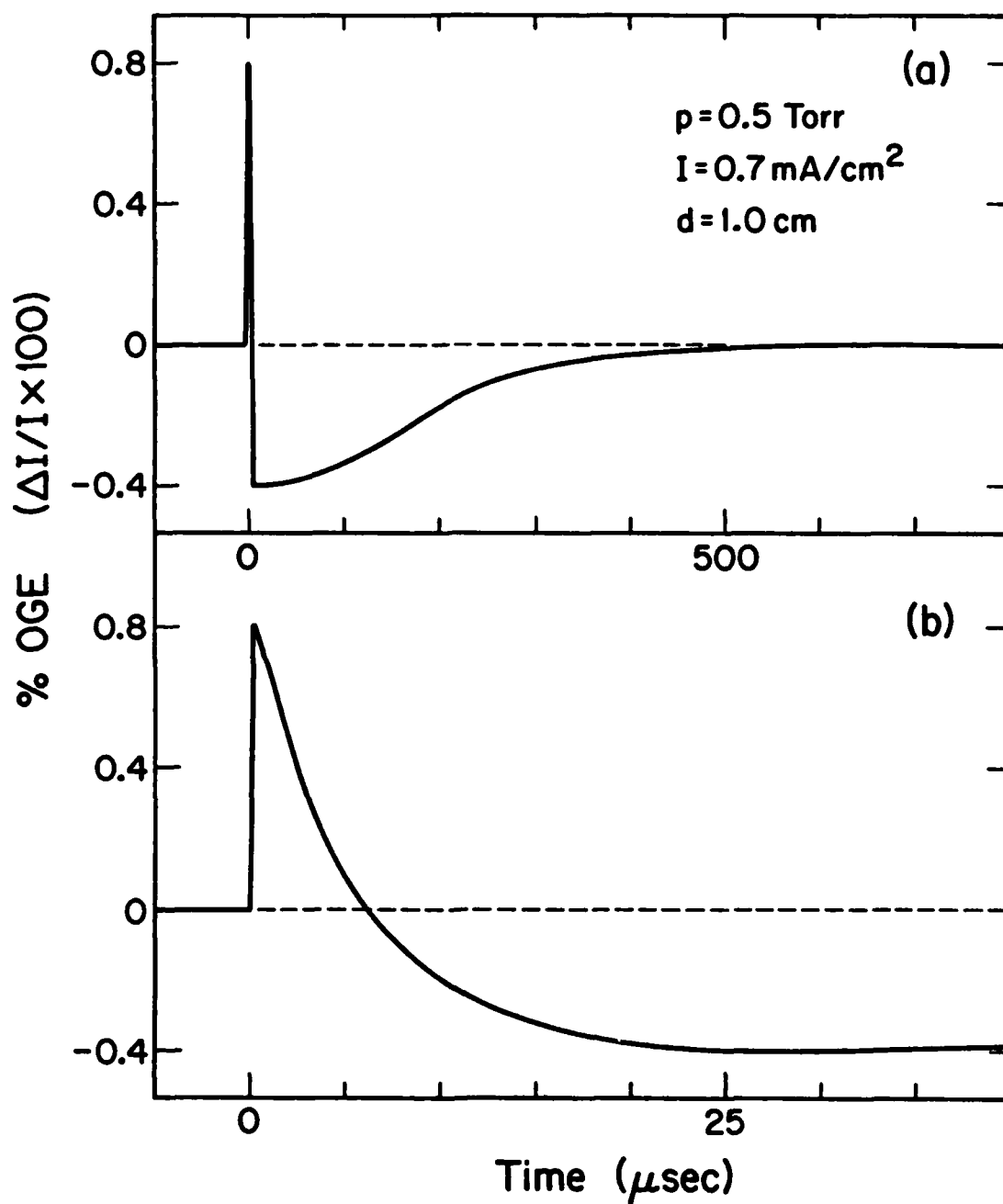


Figure 5. Time resolved optogalvanic effect at 594.5 nm in a Neon discharge with an aluminum cathode. The signal has a slow and a fast component which is visible in the lower expanded trace.

Knowledge of the important reactions and the reaction rate constants in the 388.9 nm optogalvanic effect will enable us to test cathode fall models. We will compare the laser induced fluorescence signal at 388.9 nm to the optogalvanic effect as a function of position in the cathode fall. The laser induced fluorescence signal is proportional to the number of atoms excited to the 3^3P level and hence to the number of ion electron pairs produced by associative ionization. Thus we can measure the effect on the discharge current of producing a known excess of ion electron pairs at each position in the cathode fall region. This can be interpreted as a measure of the gain provided by the cathode fall as a function of position. Such measurements can provide a direct test of the Effective Field model or other cathode fall models.¹⁴

Figure 5 is an oscilloscope trace of the 594.5 nm optogalvanic effect in Ne. The 594.5 nm transition corresponds to excitation from the $2p^53s\ ^3P_2$ metastable level to a $2p^53p$ level of Ne. Atoms excited to the $2p^53p$ levels are not associatively ionized in Ne because the reaction is endothermic by many kT. Atoms excited to the $2p^53p$ levels radiatively decay back to the $2p^53s$ levels after some mixing amongst the $2p^53p$ levels by ground state Ne atom collisions. There are large departures from Russell-Saunders coupling in Ne, so it is possible for atoms to radiate to the resonance $2p^53s\ ^1P$ level. Thus the 594.5 nm optogalvanic effect results from a net transfer of atoms from the metastable $2p^53s\ ^3P_2$ level to the resonance $2p^53s\ ^1P_1$ and 3P_1 levels.⁸

Atoms in resonance levels, although much less efficient at releasing electrons from a cold cathode, are faster at releasing the electrons. The weak but fast positive optogalvanic effect in Fig. 5 is due to an enhancement of electron emission from the cathode by vuv photons. The

characteristic time scale of the positive effect is the decay rate of resonance atoms including radiation trapping. The much larger negative photogalvanic effect results from the loss of metastable atoms and subsequent loss of electron emission from the cold cathode by metastable atom bombardment. The characteristic time scale of the negative effect is the metastable diffusion rate.

VI. Summary

The research described in this document has resulted in: (1) a better understanding of the interactions of intense laser radiation and diffuse discharges, (2) the discovery of an amplification mechanism for optogalvanic effects which is a particularly promising area for further research, and (3) the development of important new gas discharge diagnostics involving the optogalvanic detection of Rydberg atoms. The research on steady state optogalvanic effects in the positive column, described Section II, constitutes the first detailed quantitative model at the rate equation level of strong negative optogalvanic effects. The 594.5 nm effect, which is the strongest negative optogalvanic effect in Ne, was modeled over a wide range of discharge conditions. The regime studied covered the transition from a discharge sustained primarily by single-step electron impact ionization to a discharge sustained primarily by two-step ionization involving Ne metastable atoms in the $2p^53s$ configuration. The research on the 594.5 nm optogalvanic effect in Ne led to a complete characterization of the ionization and energy balance of the discharge. The research provides a theoretical framework that will be useful in modeling optogalvanic effects in many gas discharges.

The discovery of amplified optogalvanic effects has important implication for laser controlled diffuse discharge switches. These amplified effects in the cathode fall are as much as 100 times more efficient than typical optogalvanic effects in the positive column. The effects also provide a powerful new probe for studying the cathode fall. The cathode fall region will be important in laser controlled or electron beam controlled switches. The cathode fall is the most dynamic and most difficult to model region of a diffuse discharge.

The new gas discharge diagnostics which involve optogalvanic detection of Rydberg atoms will have a wide range of applications in gas discharge studies. The diagnostics are particularly well suited to research on the cathode fall region, because of the amplification of optogalvanic effects in the cathode fall. Rydberg atoms are very susceptible to the Stark effect because of the large size of the atoms and the small energy gap between states of opposite parity. Rydberg atom spectroscopy can be used to measure steady space charge fields in discharges and fluctuating electric fields from ion collisions. The size of the fluctuating fields is directly related to ion density. A wide range of electric field magnitudes can be measured by proper choice of principle quantum number. The interpretation of the linear Stark pattern is straightforward. Electric fields from tens of volts/cm to many kilovolts/cm are measureable with excellent accuracy.

Future research on optogalvanic effects should be concentrated on phenomena in the cathode fall region. Optogalvanic effects will provide the necessary experimental tools for developing a detailed quantitative understanding of the cathode fall. The cathode fall region will be important in both laser controlled and electron beam controlled diffuse discharge switches.

VII. References

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VIII. SUMMARY OF PUBLICATIONS AND PRESENTATIONS

(A) Refereed Publications

- (1) D. K. Doughty and J. E. Lawler, "Optogalvanic Effects in the Obstructed Glow Discharge," Appl. Phys. Lett. 42, 234 (1983).
- (2) D. K. Doughty and J. E. Lawler, "Model of Optogalvanic Effects in the Neon Positive Column," Phys. Rev. A 28, 773 (1983).
- (3) J. E. Lawler and D. K. Doughty, "Experimental and Theoretical Studies of Optogalvanic Effects in Neon Discharges," J. De Physique 44, 47-45 (1983).
- (4) D. K. Doughty and J. E. Lawler, "Spatially Resolved Electric Field Measurements in the Cathode Fall Using Optogalvanic Detection of Rydberg Atoms," Appl. Phys. Lett. 45, 611 (1984).
- (5) D. K. Doughty, S. Salih, and J. E. Lawler, "Two-Step Optogalvanic Effects Using Intersecting Laser Beams: A Pinpoint Discharge Diagnostic," Phys. Lett. 103A, 41 (1984).

(B) Contributed Papers in Conference Proceedings

- (1) J. E. Lawler and A. H. Guenther, "Applications of Optogalvanic Effects in Opening Switches," in Digest of Technical Papers, 3rd IEEE International Pulsed Power Conference, Albuquerque, NM (1981), p. 147.
- (2) J. E. Lawler and D. K. Doughty, "Amplification of Optogalvanic Effects in the Cathode Fall", in Digest of Technical Papers, 4th IEEE Pulsed Power Conference, Albuquerque, NM (1983), p.33.

(C) Invited Talks

- (1) J. E. Lawler participated in the Workshop on "Diffuse Discharge Switches" at Texas Tech University, Lubbock, Texas, September 23-24

(1981). He presented an invited talk entitled "Optical Control of Diffuse Discharges."

(2) J. E. Lawler participated in the Workshop on "Optical Control of Diffuse Discharges", at University of Oregon, Eugene, Oregon, December 2-3

(1982). He presented an invited talk entitled "Optogalvanic Effects".

(3) J. E. Lawler attended the Colloque International C.N.R.S. N°352

Optogalvanic Spectroscopy and Its Applications. The meeting was held June 20 - 24 in Aussois, Savoie France. J. E. Lawler presented a major invited address on the theory of optogalvanic effects entitled "Experimental and Theoretical Studies of Optogalvanic Effects in Neon Discharges." (See Ref.(3) under Refereed Papers).

(4) J. E. Lawler participated in the U.S.-F.R.G. Workshop on "Externally Controlled Diffuse Discharges" August 15 - 18 (1983) in Bad Honnef F.R.G. He presented an invited talk entitled "Metastable Atoms and Molecules in Diffuse Discharges."

(5) J. E. Lawler participated in the Symposium on Laser Spectroscopic Techniques at the A.P.S. General Meeting March 26-30 (1984) Detroit, Michigan. He presented an invited talk entitled "Optogalvanic Spectroscopy." (See Bull. of the Am. Phys. Soc. 29, 248 (1984)).

(6) J. E. Lawler plans to attend the 37th Gaseous Electronics Conf. October 9-12 (1984) Boulder, CO. He has been invited to present a "long" talk entitled "Electric Field Measurements in Glow Discharges Using Optogalvanic Detection of Rydberg Atoms".

(D) Contributed Talks

- (1) J. E. Lawler and A. H. Guenther, "Application of Optogalvanic Effects in Opening Switches", see Ref. (1) under Contributed Papers in Conference Proceedings.
- (2) D. Doughty and J. E. Lawler, "Experimental and Theoretical Investigation of Optogalvanic Effects in the Neon Positive Column", Bull. Am. Phys. Soc. 28, 177 (1983).
- (3) J. E. Lawler and D. Doughty, "Optogalvanic Effects in the Obstructed Glow Discharge", Bull. Am. Phys. Soc. 28, 177 (1983).
- (4) J. E. Lawler and D. K. Doughty, "Amplification of Optogalvanic Effects in the Cathode Fall", see Ref.(2) under Contributed Papers in Conference Proceedings.

(E) Scientific Personnel Supported

- (1) James E. Lawler, Principal Investigator
- (2) David M. Strom, Graduate Student
- (3) Douglas Doughty, Graduate Student
- (4) Elizabeth Den Hartog, Graduate Student
- (5) Eric Benck, Graduate Student